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WIND EROSION OF CRUSTED SOIL SEDIMENTS

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ABSTRACT

Saltating particles increase the rate of dust release from sediments in arid and semi-arid areas. They also break interparticle bonds in aggregated and crusted soils, thereby increasing the number of particles available for entrainment. This pilot study examines rates of erosion in relation to the flux of saltating grains for three crusted sediments of different strengths. Dislodgement of surface particles decreases with increasing crust strength, as measured by a cylindrical flat-ended penetrometer. In addition, initial dust release from craters formed by single impactors in unaggregated soil is examined in relation to the associated saltator. The volume of material removed depends linearly on the kinetic energy of the abraders.

KEY WORDS wind erosion; saltation; crusts; dust

INTRODUCTION

Loss of fine particles of silt (4–63 μm) and clay (< 4 μm) size from soils, as a result of erosion by wind, leads to a decline in the fertility of the parent soil, and a diminution in its ability to retain moisture. The presence of these particles in the atmosphere may influence climatic changes (Idso, 1981) and produce environmental hazards, such as dust storms, with associated reduction in visibility and pathogenic problems (Buritt and Hyers, 1981; Leathers, 1981). The presence of particles saltating over a soil/sediment surface may result in significant entrainment of dust, whereas there may be no entrainment by the windflow alone (Bagnold, 1960; McTainsh, 1985). Since threshold velocities increase progressively for particles finer than 80 μm (Bagnold, 1941), this release mechanism may assume an increasing significance for very fine dust particles. However, it is not known if the dislodgement mechanism is exactly similar to that seen for coarser sand grains (Willetts and Rice, 1989), or whether fluid forces play a different role when fine-grained materials are involved.

Sand grains saltating over a loose surface composed of similarly sized grains transfer momentum from the wind to the bed, enabling surface grains to be splashed up and/or rearranged. Soils contain much smaller particles than sands and most of these soil particles exist as aggregates. Cohesion between soil grains may mean that they are not immediately available for mobilization. However, the saltating grains will act to break down the bonding structure and disaggregate the surface layer. When crusting (i.e. total surface aggregation) occurs, it will serve initially to protect the underlying particles from wind erosion (aerodynamic or impact). In many arid and semi-arid regions crusts are a major structural feature of surface soils and sediments (Miller and Gifford, 1976; Guthrie, 1982). The degree of crusting is an important factor in the rate of release of fine particles from some of the main dust sources in the world, e.g. in Mali, West Africa (Nickling and Gillies, 1993). While crust formation in this situation may be seen as a positive factor in reducing wind erosion, it can be detrimental in that it decreases water infiltration, and additional runoff may increase erosion by water. Plant shoot emergence can also be restricted. The importance of the maintenance or otherwise of crusts will therefore differ depending on the management goals of the area

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in question. In arid regions, where dust generation can be a problem, the process of saltation is an important mechanism for breaking interparticle bonds in a crust, progressively disaggregating the surface and making small aggregates and individual particles available for ejection into the windflow (Chepil, 1946; Gillette *et al.*, 1974; Hagen, 1984). A supply of saltating sand or soil adjacent to the dust source is therefore a factor in maximizing the quantity of fine particles released, e.g. in the Lake Chad and Lake Eyre Basins (McTainsh, 1985). Saltating grains also have the potential to produce additional fine particles by attrition of the surface grains (Hagen and Lyles, 1985; Haff and Anderson, 1993). Eventually the crust will be ruptured and the less cohesive particles beneath exposed to wind and grain impact.

The process of abrasion in relation to different types and strengths of aggregates and crusts has been studied (Hagen, 1984; Zobeck, 1991a,b). Zobeck found that the rate of erosion depended on the quantity and energy of the abrading material and on the physical and chemical properties of the crusts.

The strength of a particular crust needs to be measured in relation to its ability to resist the abrasive action of the impacting grains. Traditionally crustal strength has been estimated by the modulus of rupture method (Richards, 1953; Gillette *et al.*, 1982), by needle penetrometer (Bengough and Mullins, 1990), by fall cone or cone penetrometer (Bradford and Grossman, 1982; Campbell and O'Sullivan, 1990), by torvane (Govers and Poesen, 1986) or by aggregate stability (Skidmore and Powers, 1982). The modulus of rupture test measures the force required to break a briquet of soil material when loaded transversely as a simply supported beam. The briquet has to be fully saturated and dried and may not be representative of thinner crusts on the same material. In addition, this technique measures a bending stress, which is not entirely appropriate for describing the relationship between crust strength and the cumulative effect of saltating particles. A needle penetrometer, has also been used to measure the resistance of the crust to root growth, but it operates over too small a surface area. The other methods provide inadequate estimates of thin surface crusts (Bradford and Huang, 1992).

This paper describes a number of experiments which formed a pilot examination of the abrasion and possible break-up of several artificially crusted sediments and of the release of surface particles from fine unaggregated material, resulting from impact by saltating grains. The experiments with unaggregated material were carried out in order to examine the effect of saltating grains on the detachment of particles

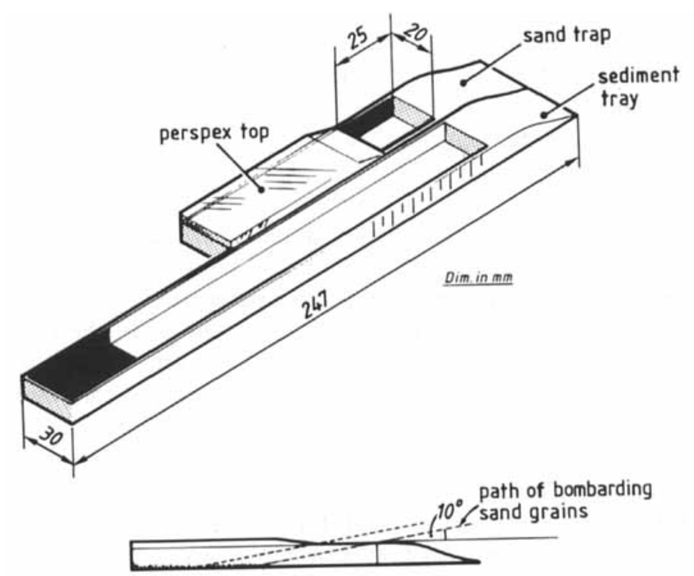

Figure 1. The sediment tray and trap

having a minimum cohesion in comparison to crusted surfaces. The crust experiments assessed the break-up of crusts of differing strengths in relation to the flux of saltating particles. The total flux delivered to a unit area of crust per unit time was derived from data collated from high-speed film, and the rate of destruction was calculated periodically by recording the alteration in surface elevation with a laser profiler. The strength of the crusts was characterized by a simple flat-ended cylindrical penetrometer test in an attempt to measure the punch shear stress over a sufficiently large numer of particles.

EXPERIMENTAL METHOD

Crusted soil

The experiments were carried out in the centre of a 12 m long wind tunnel with a cross-section of 0·5 × 0·5 m. High-speed photography was used to observe saltating sand grains bombarding three artificial crusts of differing strengths. The crusts were produced on the surface of a disaggregated very fine sandy loam soil, which has been dried and sieved to produce a population of particles with diameters < 53 μm. This was placed in a small sediment tray, 250 mm long, 20 mm wide and 10 mm deep with a streamlined nose section, and the surface was levelled.

Crusts were formed by spraying moisture on to the sediment surface and allowing it to dry out naturally. Crust 1 was lightly wetted with enough deionized water to produce a delicate crust, but not enough to induce

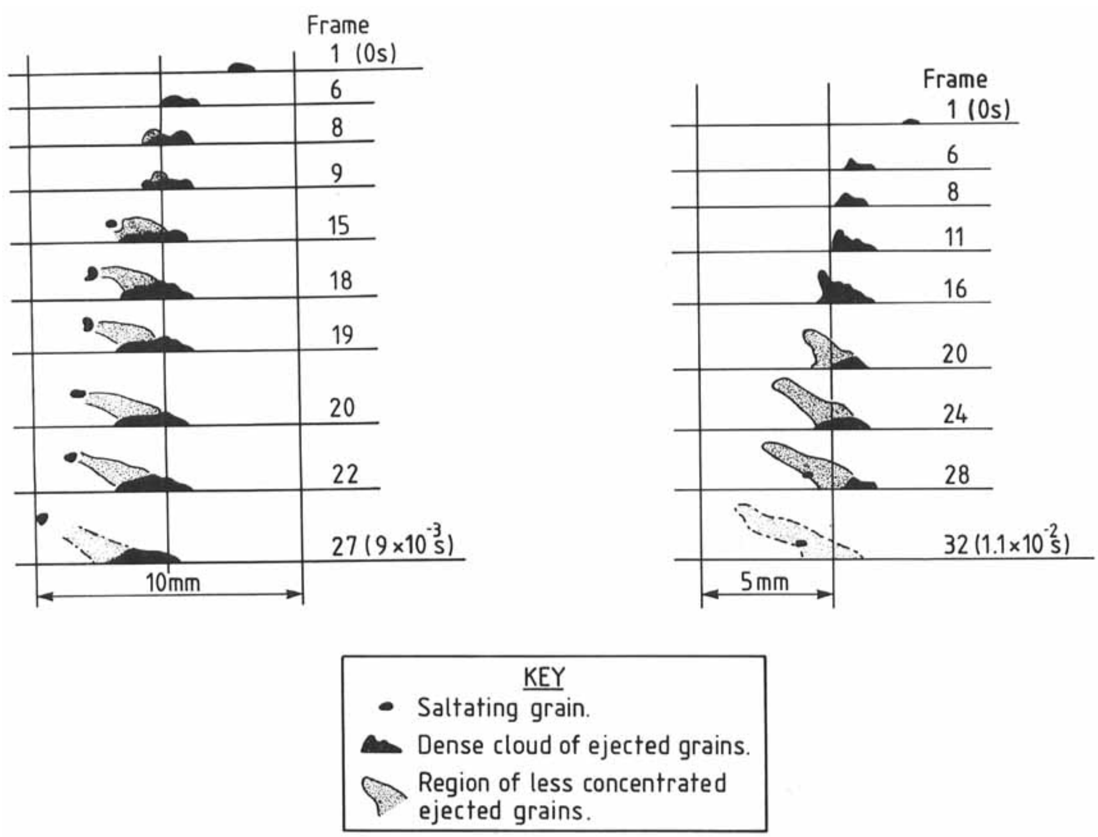

Figure 2. High-speed film sequences of single sand particles (250–300 μm) colliding with an unaggregated bed with particles < 53 μm

cracking. Crust 2 was formed by spraying with a salt solution and crust 3 was created by flooding the sediment with water. Replication of natural crusts in the laboratory poses many problems, and it is recognized that these artificial surfaces do not represent actual crusts. It is envisaged, however, that the methodology can be refined in the future to produce crusts more typical of natural conditions. The small size of the tray was advantageous for obtaining clear high-speed photographs and for accurate measurements of surface erosion, but may be enlarged to accommodate larger soil aggregates.

Prior to testing in the wind tunnel, the strength of each crust was assessed using a flat-ended cylindrical penetrometer with a diameter of 6 mm. This method was preferred to the others discussed above because it applies a load to an area of crust encompassing many grains rather than just a few grains as with a needle penetrometer. It can also be adapted for use in the field. The sediment tray was supported on the pan of a balance and the crust subjected to an increasing load until failure occurred. The penetration depth and a continuous read-out of the applied load as registered by the balance were recorded. Tests were done on portions of the crust downwind of the area that was photographed and profiled in the wind tunnel tests.

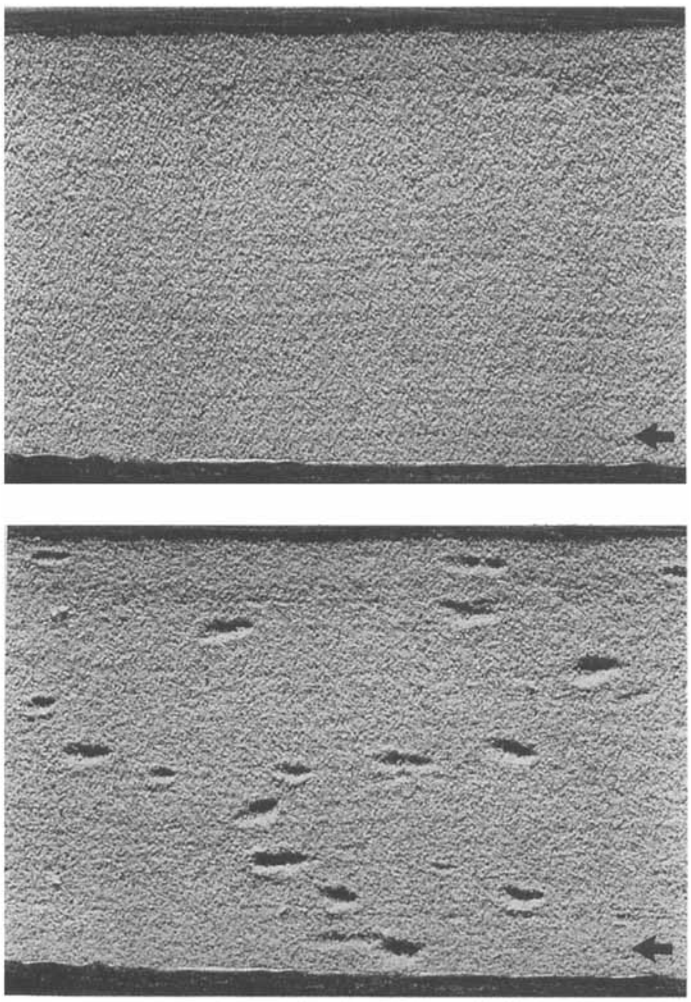

Figure 3. Plan views (2 × 3·5 cm) of the unaggregated bed. The windflow was in the direction of the arrow. (a) Before bombardment, (b) after impact by a number of sand grains

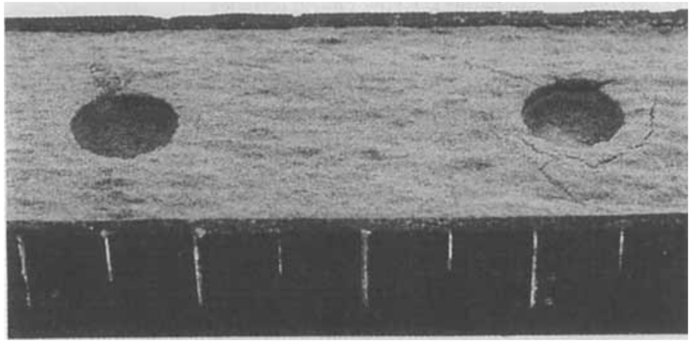

Figure 4. Crust 1 after the penetrometer test

Before and after each crust experiment, plan photographs 40 mm in length were taken of the most upwind area of the tray. Similarly, a portion of the crust (25 × 10 mm on the longitudinal centreline of the tray) was contoured using a laser profilometer with a spot diameter of 50 μm measuring on a 0·1 mm grid.

The sediment tray was positioned in the centre of the roughened wind tunnel floor 1 m downwind of a sand feed system. This supplied a narrow size band of sand grains (250–300 μm) of known mean mass via a vertical tube extending from the top of the wind tunnel to 5 cm above the floor. The constancy of the feed rate was checked by means of a sand trap (Figure 1) placed alongside the sediment tray. A perspex (plexiglass) lid at the downwind end of the trap prevented saltating grains with typical approach angles of 10–15° from rebounding, and these were weighed each time the tunnel was stopped.

The windspeed in the wind tunnel was set to give $U* = 40\,\mathrm{cm\,s^{-1}}$ for all of the experiments. Each crust was subjected to a constant rate of bombardment by saltating grains for varying periods of time depending on the durability of the crust. At the start of each experiment, and at intervals thereafter, high-speed films were taken in order that the velocities of the saltating grains could be determined. The camera was placed on a level with the crust surface and at 90° to the plane of typical saltation. A 25 mm length in the most upwind section of the tray was photographed at 3000 frames $\mathrm{s^{-1}}$ and each film lasted approximately 1·6 s.

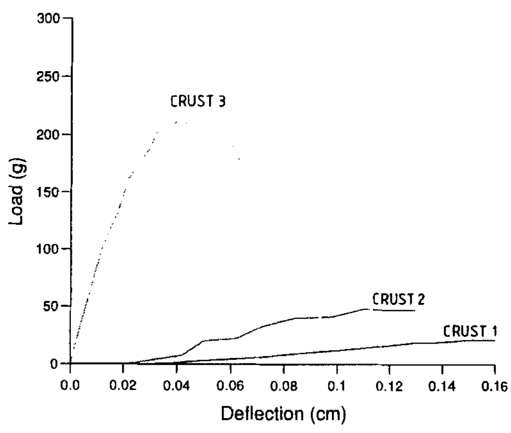

Figure 5. Plots of applied load in relation to penetration depth for crusts 1, 2 and 3

Table I. Crust characteristics

Experiment	Load at failure (g)	Thickness of crust (mm)	Punch shear stress (bar)
1	20	0·8	0·123
2	48	1·2	0·197
3	220	4·0	0·271

Unaggregated soil

Preliminary experiments using high-speed photography have shown that sand grains saltating over a surface of loose fine particles usually rebound after excavating a crater in the bed. The grains from the crater are ejected into the air as a dense cloud, which gradually disperses. The cloud either follows the rebounding grain or emerges in front of it (Figures 2a and b). The sequence of events shown in Figure 2b indicates that the ejection of fine particles to a height of several millimetres is strongly influenced by impact forces. There may therefore be no need to invoke the concept of entrainment in the wake of ascending saltating grains as suggested by Owen (1980). However, it is possible that both processes are involved in the entrainment of fine particles. The shape of the cloud was readily observed on each frame. However, because most individual particles were of similar size to the graininess of the film, single grain paths were difficult to follow.

In the experiments reported here high-speed photography and laser profilometry were used to assess the amount of material removed from a crater in relation to the energy and momentum of the impacting grain. A non-crusted fine sediment, where interparticle forces are at a minimum, erodes very quickly as a result of bombardment by saltating grains. These experiments therefore concentrated on single craters. The sediment tray was filled with a fine grain population similar to that used for the crusts, and placed in the wind tunnel. A very small number of sand grains (about 50) was used as saltators, so that only isolated craters would occur on the surface. The sand feed and camera were triggered simultaneously. If the saltating grains landed at a similar distance downwind from the leading edge of the bed to other grains, it proved difficult to identify which crater had been caused by which saltator.. Therefore, a rectangular mirror was positioned adjacent to the bed and angled at 45° so that both a side elevation of the moving grains and a plan view of the bed were seen simultaneously on high-speed film. Portions of the bed which included several craters, such as those shown in Figure 3, were profiled at 0·1 mm intervals and the volume of each crater compared with parameters of the associated impactor.

RESULTS AND DISCUSSION

Crust strength

Crust 1 proved to be a very fragile covering of weakly bonded particles. The surface was easily ruptured, but the hole produced by the penetrometer showed a coherent crust about 0·8 mm in thickness (Figure 4). Crust 2 was a stronger, slightly thicker crust, and crust 3 dried to a brick-like structure. Plots of applied load against penetration depth are shown in Figure 5. Failure of crusts 1 and 2 appears to be due to punching through the surface, whereas for the thicker crust 3, punch failure had not taken place at the maximum load. Failure occurred as radial cracking. Table 1 shows calculations for the crust strength based on punch failure, but this may be better estimated in some situations from evidence of bending and cracking of the crust. A hollow penetration device may punch through the crust more easily than a solid penetrometer, and this may therefore be a more suitable strength test for the majority of crusts.

Crust bombardment by saltating grains

Each crust was subjected to a fairly consistent bombardment of saltating grains (estimated from the trapped grains). Details of duration of the runs, bombardment rates, the impact to ricochet speed ratio

Table II. Data on the saltating grains and quantity of eroded material for the crust experiments. V_1 is the speed of the impacting grain; V_3 is the speed of the rebounding grain

Experiment	Run	Duration of run (min)	Mean $\frac{1}{2}mV_1^2$ (g cm^2 s^{-2})	Mean $\frac{1}{2}mV_3^2$ (g cm^2 s^{-2})	Mean $\frac{V_3}{V_1}$	Bombardment rate (grains cm^{-2} s^{-1})	Impact energy over profiled area (g cm^2 s^{-2})	Volume loss over profiled area (mm^3 s^{-1}) mean
1	1a	2	2·31	0·98	0·66	5·41	31·24	0·5207
	1b	1				5·81	33·55	
2	2a	3	2·70	0·99	0·61	5·54	37·40	0·0737
	2b	10				5·67	38·27	
3	3a	6	2·87	1·67	0·76	5·67	40·68	0·0293
	3b	12				5·83	41.83	
	3c	11				5·81	41·69	

for an average particle derived from the high speed films, and the estimated impact energy over the profiled area, are given in Table II. The delivery rate of 5 to 6 grains cm^{-2} s^{-1} is very low compared to the figure of 1000 grains cm^{-2} s^{-1} expected in a typical saltation cloud, i.e grains with diameters of 250 μm in a wind of $U* = 0{\cdot}5\,m\,s^{-1}$ (Anderson and Haff, 1991). Erosion rates will therefore be faster under natural conditions than indicated here.

Crust 1 was easily destroyed by the saltating sand grains. Indeed, the first high-speed film, taken after 5 s, shows ejection of soil particles (individual and aggregated) by the majority of impactors. Figures 6a and b show plan photographs of the crust before bombardment and after 3 min of abrasion. As fragments of the crust were torn away, the ruptured surface propagated downwind to produce the texture seen in Figure 6b. Removal of small pieces of crust exposes the neighbouring upwind edge of the crust to an increased rate of bombardment. Thus, weakened areas of crust tend to extend downwind. The short duration of the experiment (3 min) was a consequence of the break-up of much of the crust allowing swift erosion of the bed.

Crust 2 was stronger than crust 1, but after only 5 s approximately 50 per cent of the impactors were ejecting one or more surface grains. Any slightly upstanding aggregates had disappeared from the bed by the time the second film was taken at 3 min. Figures 7a and b show the crust at 0 and 13 min. The surface

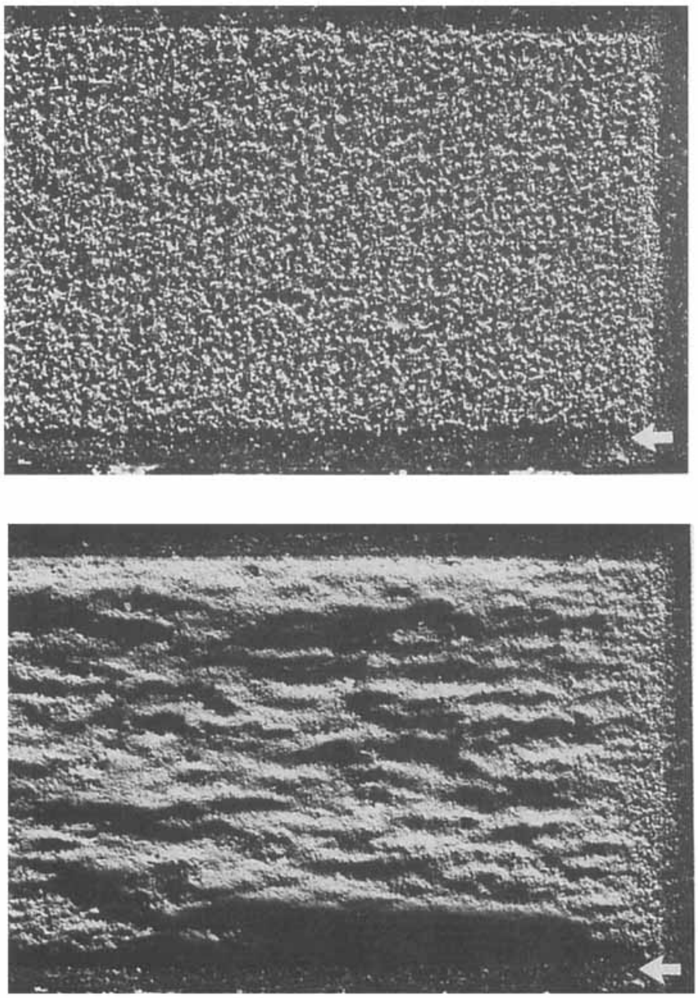

Figure 6. Plan photographs (4 × 2 cm) of crust 1, (a) at 0 min, (b) at 3 min

texture in Figure 7b indicates that, in general, zones of weakness were slower to propagate downwind than in crust 1. However, the dark area at the top of the photograph shows a ruptured portion of crust, which was weakened initially by surface cracking.

The impacting grains in the first film for crust 3 appeared to affect the surface only slightly in that no ejected grains or aggregates were observed. There was occasional evidence of surface grains being released from the bed in the two later films (at 8 and 28 min). Figures 8a and b show the surface texture of crust 3 before bombardment and after 29 min. Energy lost to the bed was less in experiment 3 (as shown by the mean impact to ricochet ratio in Table II). where the crust was more durable than in the other two experiments. The salt crust appears to absorb more energy than the delicate crust 1. It might be assumed that energy loss would be greater for the latter as many surface grains are released from the surface and initiated into motion. However, it appears that crust 2 needs more energy from the bombarding sand to break particles from the crust.

Measurements of the volume of bed material lost over the profiled area are given in Table II. A profile with a 0·1 mm grid spacing took 9 h to complete, so these were only done at the beginning and end of an

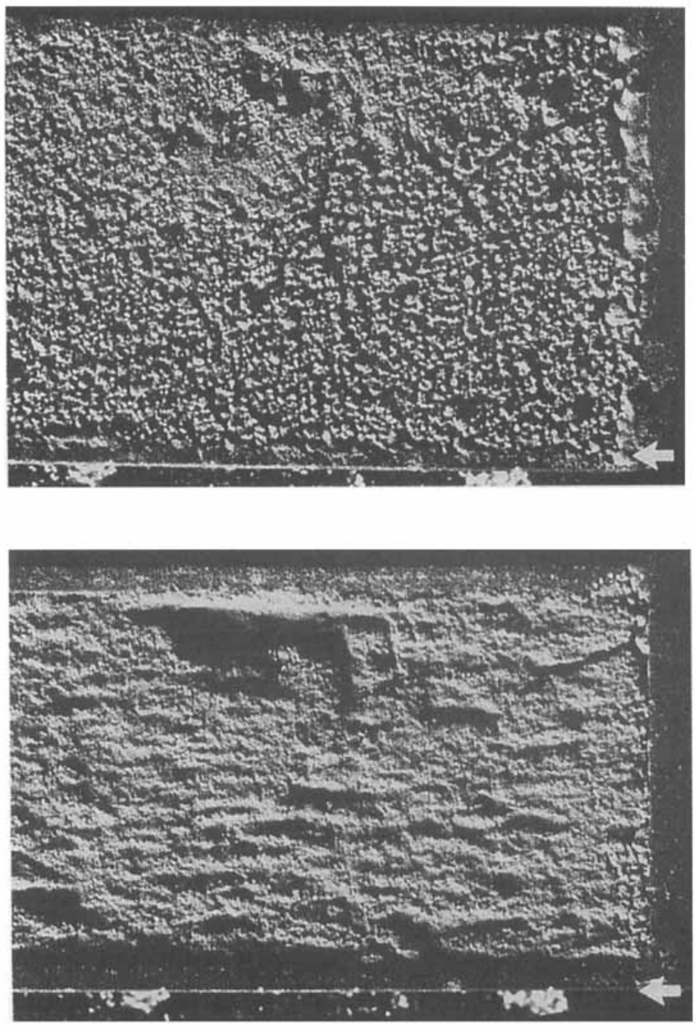

Figure 7. Plan photographs (4 × 2 cm) of crust 2, (a) at 0 min, (b) after 13 min. Note the crack at the top of (a) which has propagated downstream in (b)

experiment. Interim profiles using a coarser grid unfortunately did not provide sufficiently accurate estimates of changes in the rate of loss during different periods of each experiment. Figure 9 a, b indicates the change in elevation of crust 1 after 3 min bombardment, and a smoothing-out of upstanding features.

Unaggregated soil

The impacting grains create ovoid craters in the smooth, fine-grained surface, which are not always parallel to the wind flow (Figure 3). A typical crater shows a smaller plan area at the point of impact than at the point of exit of the saltating grain. The maximum depth of the crater is often (but not always) closer to the entry than the exit. This is in accord with the observations made by Soliman *et al.* (1976) of craters formed by ricochet of 1 inch steel spheres off dry sand. An elevated rim parallel to the forward movement of the impactor is seen on the edges of most craters. This appears more clearly on one side of the craters due to side lighting of the bed. The sand grains on the surface have left little trace of their impact and probably arrived after the tunnel had been switched off. For clarity, several crater profiles are shown in Figure 10, as positive instead of negative elevations. Their maximum depth is about 0·2 mm.

Seven craters were analysed. The volume of each was calculated from the contour profiles, and the speed

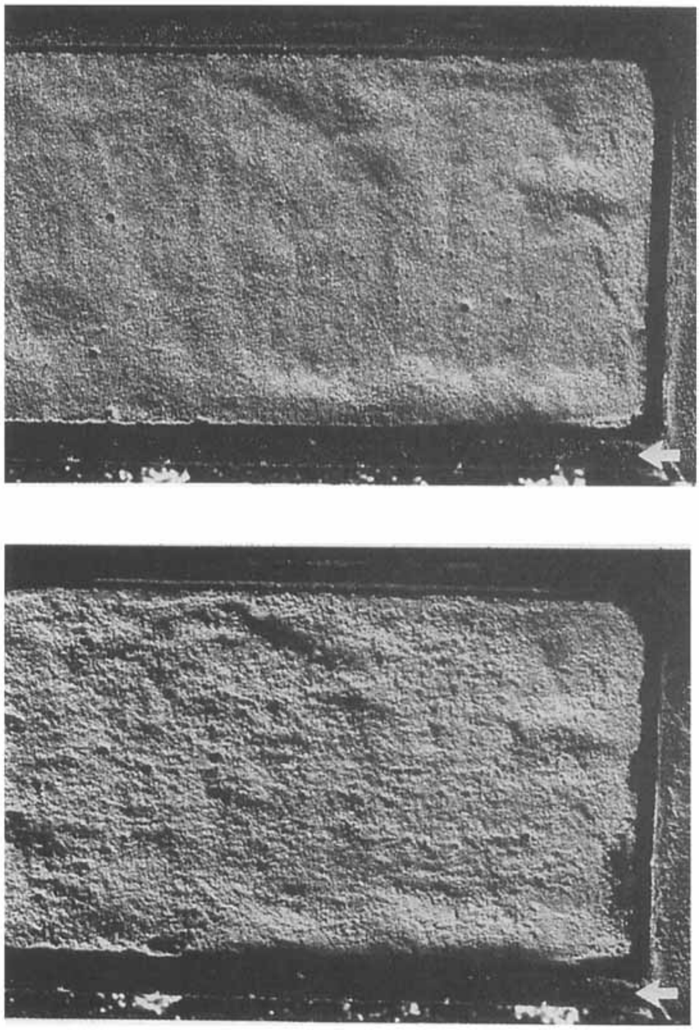

Figure 8. Plan photographs (4 × 2 cm) of crust 3, (a) at 0 min, (b) after 29 min

and angles of the associated saltator before and after impact were calculated from high-speed film images. The mean ratio of ricochet to impact velocity was lower at 0·57 than found over crusted sediments (see Table II), and may sometimes be as low as 0·40. The mean value is within the range found for sand impactors on a flat cohesionless sand surface (Willetts and Rice, 1989). Ricochet angles are typically smaller than those observed over a sand substrate, because the small surface particles are less able to deflect the trajectory of the emerging grain. Usually the ricochet angle is slightly less than the impact angle and the subsequent trajectory is closer to the bed. It is unlikely, therefore, that saltation can be sustained over unaggregated soil. However, saltating grains may be found a considerable distance from their source area in regions of patchy crust and loose exposed soil, where bombarding grains retain much of their energy over strong crusts and rebound with high enough angles to be accelerated by the wind. The velocity of the dust cloud was estimated from a number of the fastest moving particles which could be identified on consecutive frames once the cloud became sufficiently dispersed. Kinetic energy lost to the bed from the saltating grain is compared to the volume of the material removed from the crater in Figure 11a. The coefficient of correlation is 0·961. If rough estimates for the kinetic energy of the mean dust cloud are included, the plot is not changed substantially. The results support the observations of Greeley and Iversen (1985) and Zobeck (1991a) that the amount of material removed depends linearly on the kinetic energy of the abraders. When the volume of the crater is compared with the forward momentum lost to the bed (Figure 11b) the correlation coefficient is 0·862. However, because of the small sample size, no conclusions can be drawn as to whether one correlation is better than the other. For seven pairs of data, the null hypothesis that there is no difference between the

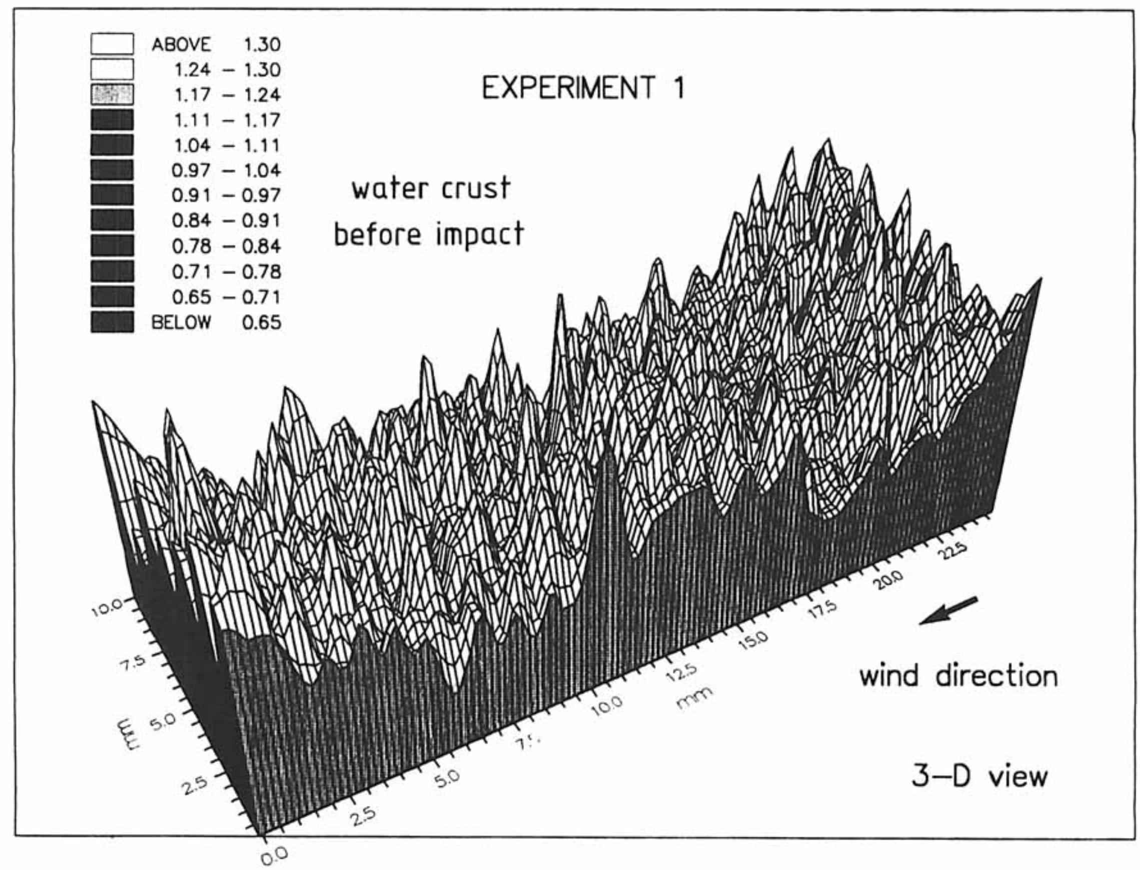

Figure 9a. Three dimensional plots of profiled surface of crust 1, (a) at 0 min, (b) after 3 min

correlation coefficients cannot be rejected at the 0·05 level. The negative intercept indicated by the linear relationship shown in Figure 11a may be partially due to an underestimation of the material displaced by the impactors. A proportion of the mobilized particles will settle back into the crater, reducing the volume of the excavated hole. This factor is reflected in Figure 10, which shows that the maximum depth of the craters is about 0·2 mm, despite the fact that the saltating grains of diameters 0·25–0·30 mm, frequently 'disappear' into the bed when viewed in side elevation on the high-speed films.

CONCLUSIONS

These experiments outline a method of estimating the volume of sediment lost due to a known bombardment rate of saltating particles for soils with different crust strengths. Measurements of crust strength reflect the extent of bonding between the particles and the amount of energy required from saltating grains to break loose small aggregates or individual particles. The weakly bonded surface of crust 1 was easily broken up by saltating grains, which rebounded with about two-thirds of their impact speed (Table II). Addition of a salt solution, as in crust 2, created a stronger crust, which needed more energy to dislodge surface particles than crust 1. Mechanical break-up of crust 3 required even more energy from the saltating grains. The strong interparticle bonds needed prolonged bombardment before they ruptured to release fine particles. Rebounding grains retained almost 80 per cent of their impact speed, indicating that they cannot easily affect the crust structure. They may, however, slowly abrade the surface by breaking off fragments of particles.

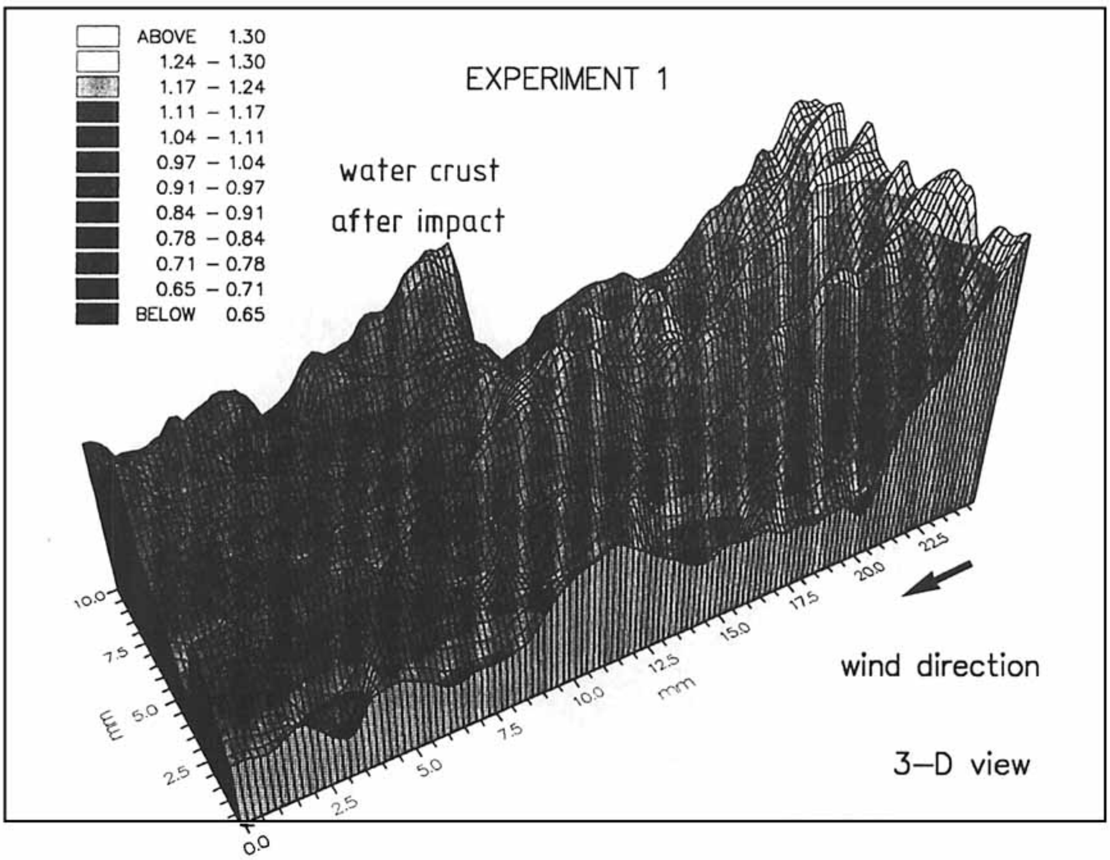

Figure 9b. Three dimensional plots of profiled surface of crust 1, (a) at 0 min, (b) after 3 min

In areas where the ground-water table is high, dissolved salts may be mobilized by capillary action, and precipitated in the surface layers. Grains cemented together in this way are likely to produce a stronger crust than those resulting from rainfall episodes. The strongest crust in the experiments reported here (crust 3) was created by evaporation of sub-surface moisture from the saturated sediment.

Once reasonable estimates are available for the amount of fine particles detached from a variety of soils and sediments by impact forces, then predictions of potential dust release in regions susceptible to wind erosion can be improved. Important additional considerations for successful models of dust generation and transport include:

(1) the areal extent of crusted and uncrusted soils – saltation is likely to die out over fine, very loosely cohesive soil; however, islands of crusted soil within these areas may extend the range of the saltating grains;
(2) a measure of crust strength;
(3) the possibility of saltating grains being present (i.e. the availability of an upwind sediment source);
(4) an estimate of the saltation flux over a period of time.

Future work on crusted sediments requires improved characterization of the crusts in terms of size distribution, aggregation, texture, chemistry and strength. An apparatus is required for measurement of crust strength in both laboratory and field. A punch test, using a hollow cylindrical penetrometer is considered to be a simple, portable method for estimating the tensile strength of the crust. Creation of crusts in the laboratory will not replicate exactly those found in the field, but a study of a range of crustal strengths due to a variety of conditions (amount of wetting, drying history, concentration of salts, soil composition

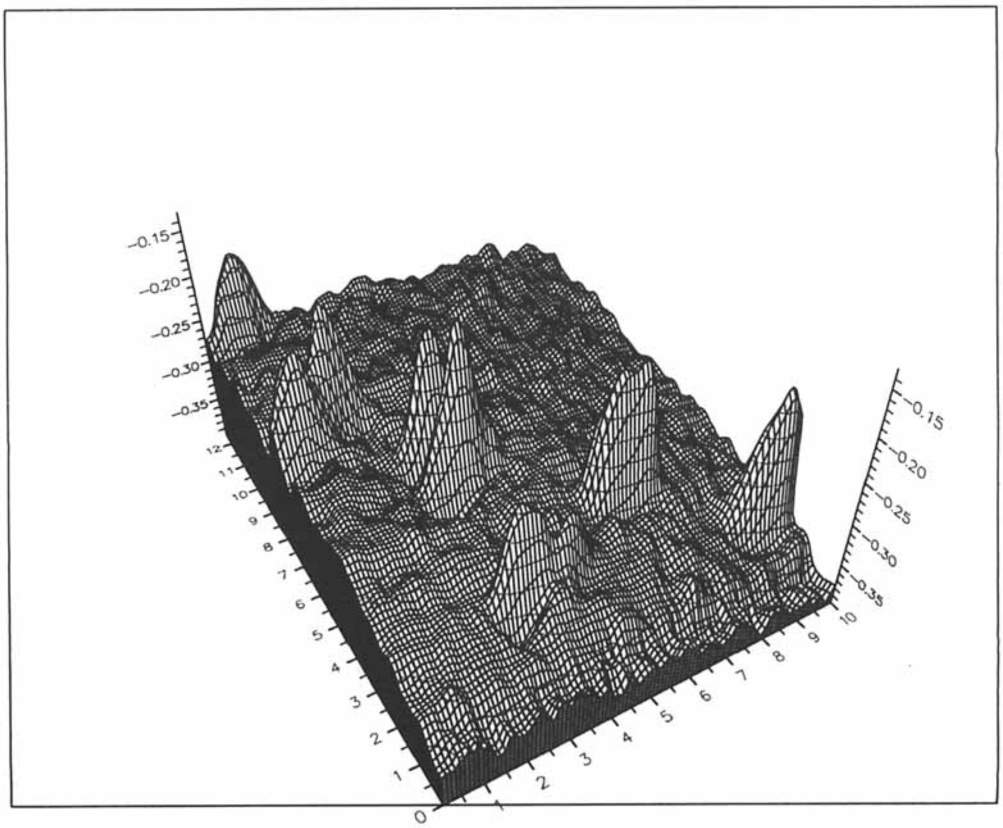

Figure 10. Three-dimensional plot of craters on an unaggregated surface. The craters are shown as elevations for clarity. Windflow is from the NE

etc.) will serve to indicate their relative durability to saltating material. In addition, the profiler could be used for a more systematic study of abrasion textures, and the surface elevation calculated at intervals to detect any changes in the rate of erosion with time, particularly as a crust starts to break up and less cohesive material becomes available for entrainment.

The crater study merits a closer examination of dust ejection by observing a smaller surface area on high-speed film with consequent increase in the image size of the entrained grains. Coupled with more accurate profiling of single craters, this may elucidate the actual dislodgement mechanism of dust release due to impact.

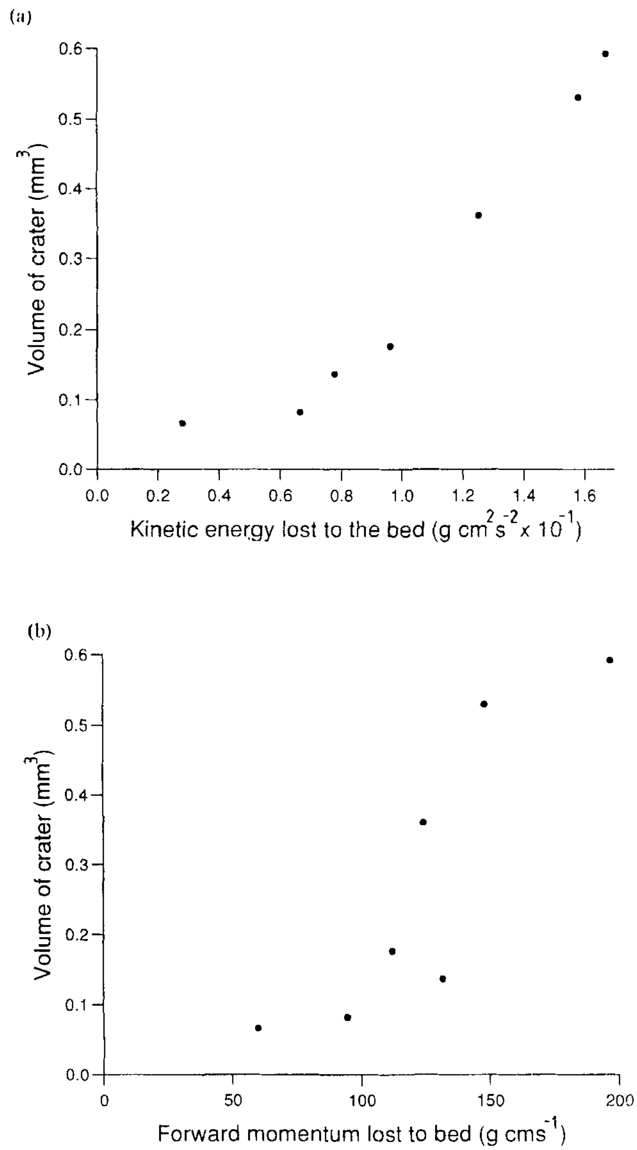

Figure 11. Crater volume in relation to (a) kinetic energy lost to the bed, (b) forward momentum lost to the bed

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